High Energy Nuclear Physics: A Summary of the Brookhaven National Laboratory Townmeeting, Jan 21-23 2001

Victoria Greene
Vanderbilt University

Barbara Jacak
State University of New York at Stony Brook

Thomas Ludlam, Larry McLerran and Thomas Ullrich
Brookhaven National Laboratory

Berndt Mueller
Duke University

Richard Seto
University of California Riverside

Steve Vigdor
Indiana University

Xin-Nian Wang
Lawrence Berkeley National Laboratory

Glenn Young
Oak Ridge National Laboratory

William Zajc
Columbia University

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1 Executive Summary

The Division of Nuclear Physics Town Meeting on Nuclear Matter and Hadrons at High Energies was held at Brookhaven National Laboratory January 21-23, 2001. A diverse group of experimentalists and theorists assembled to review recent accomplishments, challenges, opportunities and strategies for further progress in the study of the partonic structure of matter, under both normal and extreme conditions of temperature and density. The program of the meeting is included in an Appendix to this report. The meeting followed on the heels of a hugely successful and very well attended Quark Matter conference, held at Stony Brook, at which first results from RHIC received wide exposure. Both the excitement – stirred by the early indications of qualitative changes in the characteristics of heavy ion collisions from CERN SPS to RHIC energies – and some of the attendance from Quark Matter carried over to the Town Meeting. Thus, there was a distinct international flavor to the meeting, with appreciable representation of European nuclear physicists who had explored heavy-ion collisions at SPS and were planning to extend these studies at LHC when it is completed.

In addition, there was strong representation of physicists whose primary focus has been on studies of the partonic structure of hadrons and nuclei, via e-p, p-p, e-A and p-A collisions at high energies. Indeed, the Town Meeting served the important purpose of acknowledging the establishment of a broad high-energy nuclear physics community. The different elements of this community have been brought together by both physics and facility considerations. On the one hand, the unprecedented opportunities at RHIC to study polarized proton collisions and proton-nucleus collisions at energies and momentum transfers where QCD can be applied perturbatively has led to the integration within the RHIC program of a focus on quarks and gluons in cold as well as hot strongly interacting matter. Furthermore, there has been a growing recognition of the interdependence of these programs, both in experimental techniques and complementary approaches to common underlying physics goals. The behavior observed in p-p and p-A collisions forms an essential baseline against which to compare high-energy A-A collisions in search of new collective effects. Observation and characterization of a transition to a quark-gluon plasma in heavy-ion collisions would illuminate fundamental issues regarding confinement and the origin of mass, whose understanding is essential for interpreting the observed parton structure of nucleons. Analysis of the initial conditions in high-energy heavy-ion collisions has fueled theoretical consideration of universal characteristics of matter at very high gluon densities, which might be studied most cleanly in a high-energy electron-nucleus collider. Profound questions concerning gluon behavior form a common theme in all of this research.

The realization of the capability for exploration of the properties of matter at extreme energy density has over the past few decades been a vital and rapidly growing new component of the field of nuclear physics. Previously, the study of high energy nuclear physics had to use particle accelerators and detector systems that had been constructed for high energy particle physics. The field of high energy nuclear physics has now developed its own powerful new capabilities for accelerated beams and detector systems. These capabilities, coupled with significant theoretical developments, point toward a new realm of discovery in kinematic and thermodynamic regimes heretofore unheard of in any laboratory in the world. It has demanded new developments in accelerator and detector technology, as well as challenging requirements for the rapid transmission, storage and analysis of vast amounts of data. Responding to priorities set in previous Long Range Plans the U.S. Nuclear Physics Community has invested thousands of scientific man-years, as well as a substantial sum of construction funds, in the just-completed Relativistic Heavy Ion Collider (RHIC), a dedicated facility to address the core issues of this new field of science. As another long-range planning period unfolds, U.S. nuclear physics stands poised to take full advantage of this hard-won capability to make world-leading advances in our knowledge and understanding of the origins and structure of matter at its most fundamental level.

This report summarizes both the intellectual issues and physics goals at the core of high-energy nuclear physics, and the facility needs identified by this community to realize these physics goals in a timely manner. The facility needs are summarized in the recommendations below, reached by consensus during the Town Meeting. The physics justifications for these recommendations, and their resource implications, are described in more detail in subsequent sections.

1.1 Recommendations

1.1.1 Recommendation 1: The RHIC Program

RHIC has begun to have a profound impact on our understanding of the QCD structure of matter. Collisions of heavy ions will explore the transition to the quark-gluon plasma, while polarized proton collisions will reveal the partonic contributions to the nucleon spin. **We recommend full operation of RHIC with the experimental and theoretical tools needed to exploit wholly these novel and unique capabilities in a timely fashion.**

The capabilities of RHIC to provide pp, pA, and AA collisions at a variety of center-of-mass energies opens a broad physics program studying hot, dense matter and the structure of hadrons. **Full exploration of the physics program requires operation of RHIC for 37 weeks per year.**

Adequate support of experimental and theoretical researchers

is essential to realizing the physics promise of this new facility to address fundamental questions of strong interactions.

It is important to pursue targeted opportunities for near-term upgrades to the RHIC detectors, thus extending the kinematic and physics reach of the present program.

1.1.2 Recommendation 2: The Next Generation of Accelerators and Detectors

A vigorous R&D program to pursue the next generation of accelerator and detector developments needed to elucidate the QCD structure of matter. Two initiatives of primary interest are: a) a luminosity upgrade at RHIC to study rare probes of the quark-gluon plasma; b) a high-luminosity electron-ion collider to characterize matter at high parton density and measure new spin-dependent features of nucleon structure. Both initiatives require development of high intensity electron linacs with energy recovery, as well as innovative detection techniques.

It is anticipated that full utilization of RHIC will provide data by 2005 that demonstrates a transition to the quark-gluon plasma (QGP) phase of strongly interacting matter. Such an achievement would stimulate the need for a more detailed characterization of the structure of the deconfined phase and the implications of chiral symmetry restoration, requiring study of selective signals that remain elusive with the present accelerator and detectors. An order of magnitude luminosity increase for nucleus-nucleus collisions at RHIC, coupled with appropriate detector upgrades, would make it feasible to develop new probes of the temperature and parton composition of the QGP, based on the production of hadrons with multiple heavy quarks and on electroweak production processes at a high mass scale. Other detector upgrades would be needed to improve background suppression for such QGP probes as open charm or low-mass dilepton production. One focus of detector R&D would be optimization of tracking with high vertex resolution and rate capability. The luminosity upgrade for ion beams requires development of high-energy electron cooling, with a high-current 50 MeV energy recovery linac for the electrons. A luminosity upgrade could also extend the physics reach of the polarized pp collision program, facilitating investigation of the Goldstone boson content of the nucleon sea and a significant search for quark substructure in parity-violating jet production.

A new electron-ion collider facility, covering the CM energy range from 30 to 100 GeV with luminosities of at least $10^{33} cm^{-2} s^{-1}$, would extend the spectacularly successful exploitation of deep inelastic scattering into new regimes of profound interest. High-energy eA collisions would probe strongly interacting matter at unprecedented gluon densities, where QCD suggests the onset of a new, Bose-condensed state. Deep inelastic scattering of polarized electrons from polarized beams of protons or light ions would extend measurement of the nucleon spin structure to the abundant partons that each carry a small fraction of the nucleons momentum. The collider geometry would offer the crucial capability of complete event reconstruction in hard polarized scattering processes, probing the transition from individual parton densities to the full nucleon wave function. A detailed plan for a facility meeting these physics goals requires substantial R&D on electron cooling and polarized electron source technology, and on detector integration within the constrained accelerator lattice. One possible implementation under consideration would call for adding a 10 GeV high power electron linac to RHIC.

R&D funding of several million dollars per year is needed to address the above technical issues on a five-year time scale. The results of that R&D, combined with emerging physics results from RHIC and from the present generation of nucleon spin structure experiments, will guide development of more detailed proposals for these two exciting facility initiatives.

1.1.3 Recommendation 3: Massively Parallel Computing

The development of multi-teraflop massively parallel computing facilities for lattice gauge theory and other problems in nuclear physics provides unprecedented opportunities for progress in theoretical physics, which should be pursued.

Large scale computing allows numerical solution to a wide variety of problems of interest for high energy nuclear physics. The development of new machines designed to do massively parallel computing could increase the resources applied to such problems by at least an order of magnitude.

Lattice gauge theory computations are largely limited by computational speed. Problems which involve light mass fermions are very time consuming, and to get reliable quantitative predictions for masses which correspond to physical values of the quark mass requires greater computational power. For example, whether or not there is a first order phase transition between hadronic matter and the quark gluon plasma is not known for physical quark masses. Computations of particle masses and matrix elements also rely crucially on using correct masses.

Hydrodynamic and cascade simulations of heavy ion collisions are notoriously complicated. Many of the interesting phenomena associated with heavy ion collisions involve non-central collisions, and simulations severely stress the limit of current computational power.

Problems such as Green's function Monte-Carlo, and hydrodynamical simulation of supernova explosions are also currently limited in accuracy and scope by computer power.

The cost of building machines with ten teraflop capability is about \$1.5 M per teraflop. Proposals for such machines are being prepared by Brookhaven, Jefferson Lab, and Fermilab as a part of the DOE Office of Science initiative, Scientific Discovery through Advanced Computing (SciDAC).

1.1.4 Recommendation 4: Physics at the LHC

A focussed program, involving moderate resources, of participation in the heavy-ion experiments at the LHC should be pursued.

In 2006, the Large Hadron Collider (LHC) at CERN will be the highest energy accelerator operating on Earth. Its approved experimental program includes a strong heavy-ion collision component, with one dedicated heavy-ion experiment, ALICE, and an additional heavy-ion program in CMS. LHC data from heavy-ion collisions at unprecedentedly high energies will thus begin to complement the Relativistic Heavy Ion Collider (RHIC) scientific program shortly after 2006. Even a moderate US participation in the LHC heavy-ion experiments will have a significant impact on the LHC program. At the same time, this will lead to a very positive feedback on the understanding of RHIC physics and dynamics.

The center of mass energy for heavy-ion collisions at the LHC will exceed that at RHIC by a factor of about 30. This provides exciting opportunities for addressing unique physics issues in a completely new energy domain:

- LHC-energy heavy-ion collisions provide a unique opportunity to study the properties and dynamics of QCD in the classical regime. The density of the low x virtual gluons in the initial state will be high enough for saturation to set in so that their subsequent time evolution is governed by classical chromodynamics.

- Due to the higher incident energy compared to RHIC, semihard and hard processes will be a dominant feature at the LHC and gross properties of the collision can be reliably calculated using perturbative QCD.

- Very hard strongly interacting probes, whose attenuation can be used to study the early classical chromodynamic and thermalization stages of the collision, are produced at sufficiently high rates for detailed measurements.

- Weakly interacting probes, such as direct photons, $W^{\pm}$ and Z^0 bosons produced in hard processes, will provide information about nuclear parton distributions at very high Q^2. The impact parameter dependence of their production is sensitive to the spatial dependence of shadowing and saturation effects.

- Compared to RHIC, the ratio of the lifetime of the quark-gluon plasma state to the time for thermalization is expected to be larger by an order of magnitude so that parton dynamics will dominate the fireball expansion and the collective features of the hadronic final state.

A complete picture of heavy-ion collision dynamics at high energies requires the analysis of the complementary information gained at both RHIC and the LHC. US participation in both programs is essential for securing a stable place at the frontier of heavy-ion research for our scientific community.

1.1.5 Recommendation 5: Outreach

University-based research groups and laboratories are the lifeblood of our field.

The federal investment in the university infrastructure has traditionally been a major source of funding for science education. Continued federal support with appropriate matching from State and educational institutions is essential to take full advantage of the opportunities to immerse young scientists into frontier scientific environments and to train future generations of nuclear scientists for basic research and national needs.

Science education and literacy are critical to the future of the nation.

Education and outreach activities to K-12 and society-at-large need to constitute a strong component of all new major institutional research proposals. Educational institutions in partnership with Federal funding agencies need to identify additional resources for these essential activities.

The community should consider the establishment of an "Educational Fellowship", modeled after the APS "Congressional Fellowship" program, to be supported by APS/DNP and other Federal funds. This program would be designed to encourage and support interested scientists to develop new educational initiatives at all levels.

The social diversity in the nation should be reflected in its scientific force.

Efforts to recruit, train and retain underrepresented elements of the work force into the study of science must be increased at all levels of education, research and funding.

2 The Scientific Goals of Nuclear Physics at High Energy

The goal of high-energy nuclear physics is development of a workable basis for understanding strong interactions at the partonic (quark-gluon) level. It is these interactions that normally confine many quarks and gluons inside protons and neutrons, and that account for nearly all of the mass of ordinary matter. Just how the interactions determine the structure of matter at this most fundamental level remains mysterious, because the underlying theory of the interactions – Quantum Chromodynamics (QCD) – is notoriously difficult to solve in most cases of interest. Thus a focused effort in both theory and experiment is required to reach our main goal. At present three discernible areas of high interest and great promise are being pursued.

In the first, we attempt to illuminate the nature of quark confinement and the origin of mass by inducing a transition in matter to a form where these very characteristics are radically altered. To reach this altered form – the quark-gluon plasma – we must create strongly interacting matter in the laboratory at least fleetingly at the enormous temperatures attained in the earliest instants of the infant universe, just after the "Big Bang". This recreation requires collisions of beams of heavy nuclei at very high energies, and has been the primary motivating factor behind the construction of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory.

The second focus is on the behavior of gluons – the self-reproducing force carriers ultimately responsible for confinement – when they are assembled at very high density. The gluons may then coalesce into a simple, strongly correlated ensemble that leads to a universal behavior of all strong interaction processes in the high-energy limit. The search for this universal gluonic matter requires colliding a variety of beams at high energies, with the greatest gluon densities exposed when at least one of these beams contains heavy ions.

The third focus, representing the bulk of the research carried out to date, employs simpler interactions at very high energies (*e.g.*, deep inelastic scattering of electrons from protons) to reveal the underlying quark-gluon structure of the naturally occurring strongly interacting particles (called hadrons, and including protons, neutrons and mesons). The nature of QCD implies that the partonic structure of hadrons can only be reliably extracted from hard, high-energy collisions, typically requiring minimum beam energies of several tens of GeV. The higher the energy the more fine-grained, detailed and extensive the information on the partonic structure can be.

Returning to the first goal for this subfield, we seek to study matter at energy densities believed to have existed in the first 10 microseconds after the Big Bang. In experiments currently being carried out at RHIC, head-on collisions of high-energy heavy nuclei will produce matter at temperatures 100,000 times that of the interior of the sun. These conditions are expected to be sufficient to create a state of matter called the quark gluon plasma (QGP). A QGP is similar to the hot plasmas of electrons, photons and nuclei which surround stars. The difference is that this plasma is much hotter, and its constituents are quarks and gluons.

Because the energy density produced in heavy-ion collisions at RHIC is more than an order of magnitude greater than that inside an atomic nucleus, and is even greater than that inside a single proton, the protons and neutrons in the collision dissolve into a "soup" of their partonic constituents. This QGP is a new form of matter, in that it has never been unambiguously identified. We now have the unprecedented opportunity at RHIC to investigate this matter of the early universe in the laboratory, and to test our ideas of its properties. In the transition to the QGP, quarks and gluons, normally confined by very strong forces to reside inside the neutrons and protons, are released and become free to move throughout the volume of the plasma. It is also believed that in this transition, the mass of the neutrons and protons is largely converted into energy of quark motion. Understanding this change may clarify both the origin of confinement and the origin of most of the mass of ordinary matter.

The second goal of this field is to understand the global features of strong interactions in the limit of large collision energy, where collisions become dominated by the influence of the very high gluon density. This goal is complementary to the thrust of particle physics, which concentrates on rare processes to test the fundamental QCD force between two partons. In contrast, our focus is on the still mysterious many-parton features of QCD found in hadrons and nuclei. Some of the open questions are: How does the cross sectional area of a strongly interacting particle change as the collision energy becomes large? How likely are high energy collisions of strongly interacting particles to produce matter, and how does this probability change with energy? What is the origin of the quark and gluon content of such particles? What are the initial conditions for a quark gluon plasma produced in high energy heavy-ion collisions?

Some theories suggest that the high energy density gluons, which may be responsible for the bulk properties of strong interactions, form a Bose condensate, a form of cold matter involving very many highly correlated particles. This type of condensate is responsible for superconductivity and superfluidity in ordinary matter. This high energy density matter is believed to have glassy properties and is called a Color Glass Condensate (where "color" is the name given to the intrinsic property of quarks and gluons that allows them to exert and to feel strong forces).

In addition to their usefulness in exposing matter under extreme conditions of temperature and density, a third use of high energy beams is to provide the resolving power needed to probe how the point-like quarks and gluons are distributed inside ordinary nuclear matter, including protons and neutrons. The dominant role of the intense interactions among the constituents is unique in studies of composite particles, and it raises many profound questions about the structure of matter at this most fundamental level. Examples of important questions still to be answered are: How do quarks and gluons cooperate to build up the intrinsic spin of a proton? To what extent do the abundant quarks and antiquarks in a proton form collective sub-assemblies such as pi-mesons, which play a pivotal role in breaking basic symmetries of the strong interaction? RHIC also brings unprecedented capabilities to the assault on such questions: For the first time, collisions of spin-polarized proton beams can be studied at sufficiently high energy to permit simple interpretation in terms of collisions of quarks and gluons. Their study is possible with relatively minor modifications of existing RHIC detectors, modifications already under way.

3 The Significance of High Energy Nuclear Physics for Science and Society

One of the oldest goals of science is to understand the nature of matter. In the early part of this century, this pursuit led to the creation of quantum mechanics, which forms the dynamical context of all our theories of subatomic phenomena. This discovery profoundly changed the way we view the world around us, not only in the basic sciences, but also in engineering and even in philosophy and literature. Quantum mechanics has provided the basis for comprehending and utilizing matter at the atomic level and below, and has thus allowed the development of the technologies that shape the modern world. Later in the century, the properties of atomic nuclei and their interactions were revealed and the science of nuclear physics was born. This subject had profound implications for astrophysics, since the stars including our sun get their energy from nuclear reactions. The wide array of chemical elements are created from hydrogen and helium in these gigantic stellar reactors and expelled back into interstellar space upon their eventual explosive demise. Comprehending and utilizing nuclear processes plays an enormous role in engineering, medicine and national defense.

More recently, it has been shown that the standard model of strong and electroweak interactions describes fundamental interactions up to energy scales of several 100 times the mass of the proton. The fundamental particles of the standard model are quarks and leptons and they interact via the exchange of photons, gluons, and heavy bosons. This fundamental synthesis of the laws and phenomena of nature is one of the great triumphs of science.

High-energy nuclear physics has as its central focus the study of matter at high energy density, and follows a similar path that led to progress in physics during the last century. We study matter not only as it is realized in normal atoms and nuclei, but also as it behaves under extreme conditions. The resulting information and insights will enlighten us about properties of quarks and gluons inside hadrons and the manner in which they become confined and produce their observed mass.

The study of a quark gluon plasma (QGP) extends our range of investigation of the properties of nuclear matter by an order of magnitude higher in energy density. It is also now believed that the universal high-energy limit of strongly interacting matter is due the existence of a new form of ultra-dense gluonic matter. The discovery of these states of matter and their inclusion into the standard model would be an enormous intellectual advance. In addition to providing a limiting case for dense gluonic matter it may hold the key to the physics that establishes the properties of normal hadrons and nuclei.

Characterizing nuclear matter at high energy is by its very nature fundamental, but it also has relevance to other areas of science. For example, quark-gluon matter has a rich phase structure at high density and low temperature, with a variety of different superconducting and superfluid phases. This structure may ultimately aid understanding astrophysical phenomena such as neutron stars and gamma ray bursts. The theoretical explanation of the high-energy limit of strong interactions will help us understand the origin and interactions of the highest energy cosmic rays, including neutrino interactions.

In cosmology, an outstanding problem is the origin of matter. That is the big bang should have produced matter and anti-matter in equal amounts. Fortunately for us there is a vast excess of matter. The emergence of this excess may have occurred at the electroweak phase transition at a temperature about 1000 times higher than that which can be studied at RHIC. The mechanisms which produce the matter excess in the electroweak plasma have a close correspondence to processes of the quark-gluon plasma, and much can be learned about them by the experimental and theoretical studies of hot quark-gluon matter.

4 Recent Accomplishments of High Energy Nuclear Physics

4.1 First Collisions at RHIC

Within the 6 months of completion of RHIC, first collisions were achieved; detectors commissioned and significant scientific results were published- a remarkable technical and scientific achievement.

A very important milestone was reached last year in the study of relativistic heavy-ion physics with the initiation of the RHIC program. The

Relativistic Heavy Ion Collider (RHIC), which began construction in 1991, was completed and commissioned during the past year. It opened up a new frontier with an increase in center of mass energy of little more than an order of magnitude over the past experiments and will allow studies of a new regime in the QCD phase diagram.

The first data taking run in 2000 lasted for 3 months, during which the machine reached 10% of its designed luminosity at 130 GeV/nucleon center of mass energy in Au-Au collisions. A successful commissioning of polarized protons was also done with protons in one ring of RHIC. All four detectors (BRAHMS,PHOBOS, PHENIX and STAR) were in operation during the run and about 10 million events were collected between the 4 detectors. Figure 1 shows an event display of one of the early events from the STAR detector.

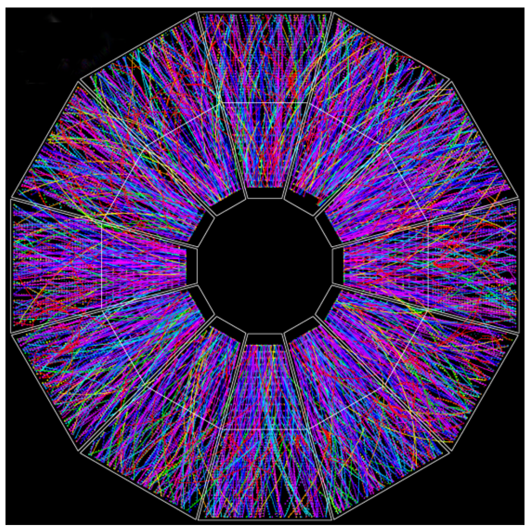

Figure 1: A event display from STAR showing a beam's eye view of the TPC.

4.1.1 STAR

The **S**olenoidal **T**racker **A**t **R**HIC (STAR) is a large acceptance detector capable of tracking charged particles and measuring their momenta in the expected high multiplicity environment. It is also designed for the measurement and correlations of global observables and the study of hard parton scattering processes. Viewing the detector from inside to out the first element is the silicon vertex tracker (SVT) which consists of 3 layers of silicon drift detectors. It allows the measurement of the primary vertex with high accuracy and the reconstruction of secondary vertices. The main tracking detector is a cylindrical TPC located inside of a solenoidal magnet covering 4 units of pseudorapidity ($|\eta| < 2$) with full azimuthal coverage. The last layer of the detector is a Pb-scintillator sampling electromagnetic calorimeter which will be used to trigger on transverse energy and measure jets, photons, and electrons. It consists of a barrel ($|\eta| < 2, \Delta\phi = 2\pi$) and one endcap. Two additional TPCs located in the forward regions extend the STAR acceptance to near beam rapidities. A small acceptance Ring Imaging Cherenkov detector (RICH) and time-of-flight system (ToF) enhance the particle identification capabilities at mid-rapidity. The year 2000 run was performed with the TPC and RICH only. Both forward TPCs, the SVT, ToF, and 25% of the barrel EMC are in place for the 2001 run.

4.1.2 PHENIX

The PHENIX detector is composed of 4 spectrometers optimized for detecting and identifying electrons, muons, photons and hadrons in a limited pseudorapidity range. Multiple detector subsystems are used in the two central arms, yielding good momentum resolution and particle identification. Of particular note is redundancy in electron identification capabilities, giving a total e/π rejection of better than 10^{-4}. Excellent hadron identification via Time Of Flight (TOF) is available over a small angular range. Muons are detected in two arms covering forward and backward rapidities, where the muons have a kinematic boost enabling them to be separated from the copious hadrons produced in the collisions. During the year 2000 run, about 1/2 of each of the central arms were instrumented. The central arms and one of the muon arms will be completed for the 2001 run. The second muon arm will be completed in the year 2002.

4.1.3 PHOBOS and BRAHMS

PHOBOS, one of the two smaller detectors, is primarily composed of silicon and is optimized for low-pt measurements. BRAHMS specializes in measuring the fragmentation region of the collisions. Both of these detectors were substantially complete during the past run, with completion expected before the 2001 run. In the 2000 run, about 10M events were collected among the 4 detectors, allowing for a good start on the physics program. About 2 orders of magnitude more events are expected in 2001.

4.2 First Physics Results from RHIC

Only 4 months after the first RHIC run, physics studies yield a wealth of new and interesting results, including the observation of near hydrodynamic collective behavior (radial and elliptic flow) in early evolution and first evidence of large p_T hadron suppression.

The Relativistic Heavy Ion Collider, RHIC, which began construction in 1991, was completed and commissioned during the past year. The first data taking run in 2000 lasted for 3 months, during which the machine reached 10% of its ultimate (i.e. design) luminosity at 130 GeV/nucleon center of mass energy in Au-Au collisions.

Analysis of the data has taken place in a most timely fashion, and we have already learned many new things about the collisions.

4.2.1 Multiplicity

The first measurement made by PHOBOS and PHENIX is the particle multiplicity, which indicates that the yield per participating beam nucleon is higher by about 70% than at SPS/CERN, as shown in Fig. 2

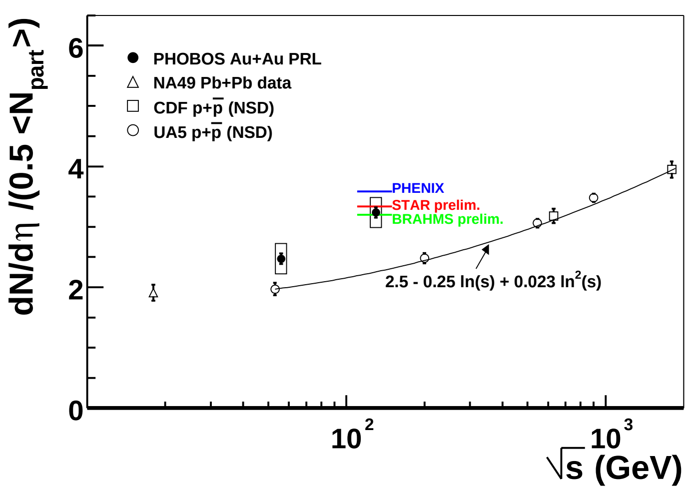

Figure 2: Energy dependence of $0.5 dN_{ch}/d\eta/N_{part}$ for central Au+Au and Pb+Pb collisions as compared to pp and $p\bar{p}$ collisions

The yield per participant increases with centrality (PHENIX). Depending on the thermalization time, the data imply that the energy density is considerably higher at RHIC than at SPS/CERN. Various theoretical predictions were compared to the dependence of multiplicity upon centrality, as shown in Fig. 3. These various models all assume hard production processes for gluons, but differ in their description of the low momentum cutoff imposed on these production processes.

4.2.2 Elliptic Flow

STAR has measured the azimuthally asymmetric (known as elliptic) collective flow of particles in peripheral and semi-central collisions, and found it to

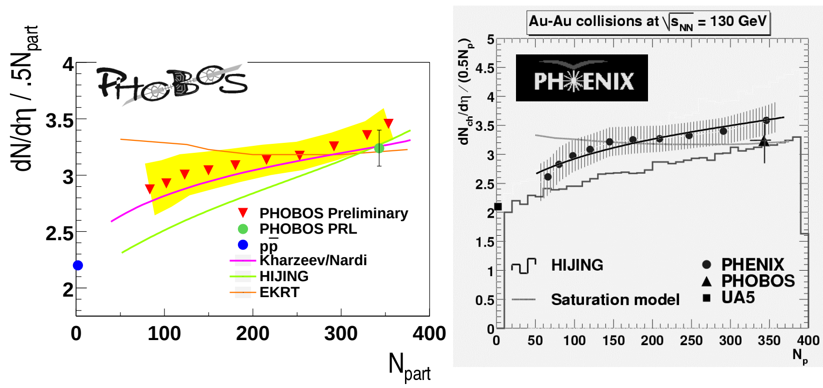

Figure 3: The dependence of multiplicity upon centrality. There is good agreement between PHOBOS and PHENIX.

be rather large; $v2 \sim 6\%$. This measurement is in agreement with a similar one by PHOBOS, and PHENIX measures similar effects. This is interpreted to indicate a high degree of thermalization, taking place early in the collision and building up pressure while the asymmetry of the colliding system along the impact parameter direction is present. Theoretical models using hydrodynamical descriptions assuming early thermalization can describe the data. In Fig. 4, the data on v2 is plotted along with a a theoretical computation of the asymmetry. The agreement between theory and experiment is good except for the most peripheral collisions, where the assumptions underlying the theoretical computation break down.

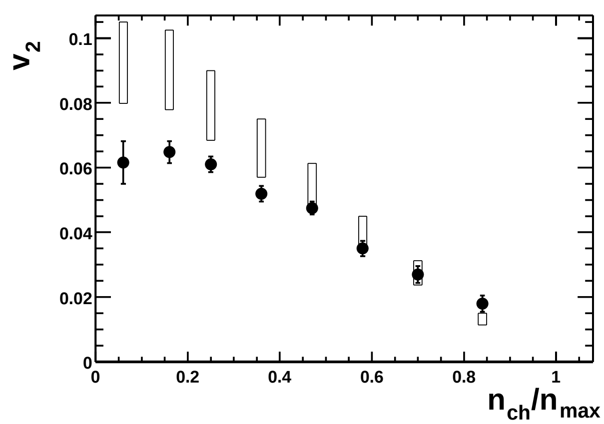

Figure 4: The centrality dependence of v2 of STAR as compared to the hydrodynamic values.

4.2.3 Pion Interferometry

STAR has also made an initial measurement of Bose-Einstein correlations, yielding size parameters of approximately 6 fm, similar to that measured at SPS/CERN. These measurements yield information about the space-time volume in which the system was produced. First measurements show very little to no change in these values from AGS and SPS measurements, as depicted in Fig. 5. This surprising result together with the findings on radial flow might indicate a very sudden freeze out.

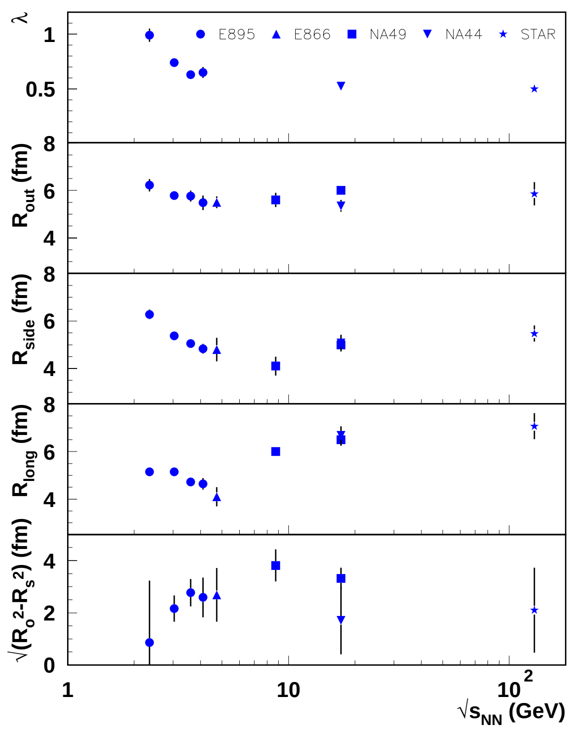

Figure 5: The world's data on HBT interferometry for heavy ion collisions.

4.2.4 Protons and Anti-protons

Early measurements, also from STAR indicate that the $\overline{p}/p$ ratio at midrapidity at RHIC in collisions at $\sqrt{s}$ =130 GeV is 0.6, in contrast to the SPS where it is 0.07. This ratio is shown in Fig. 6, along with ratios of abundances of other identified particles. This measurement has been confirmed by BRAHMS. This is interpreted as evidence that one has produced matter at RHIC with a low ratio of net baryon number to energy density.

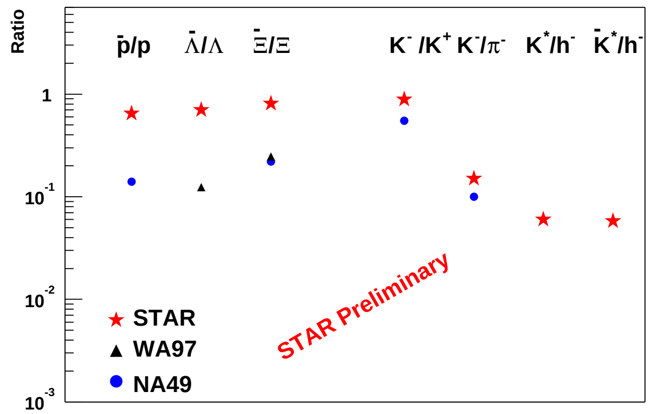

Figure 6: Ratios of abundances of identified particles produced at RHIC in central collisions.

One of the surprises of the early results from PHENIX is that at intermediate transverse momenta, the protons and anti-protons begin to dominate the spectrum over pions. This was unexpected and may indicate strong collective effects in the matter produced in these collisions, or perhaps new phenomena. (Fig. 7)

4.2.5 Jet Quenching

In the STAR and PHENIX experiments, measurements have been made of particle spectra as a function of transverse momenta. These data show that the production of hard particles is reduced by about one order of magnitude at large $p_\perp$ relative to what was expected from simple superposition of incoherent pp collisions. This is interpreted as jet quenching, the phenomenon that a produced hard parton would rescatter on the media in which it is produced. Such a phenomenon has long been predicted by theoretical studies of parton propagation in a dense QCD medium. These measurements should eventually provide direct information about the times at which matter was produced in heavy ion collisions and the energy densities at these early times. (Fig. 8)

4.2.6 Particle Abundances

The ratios of abundances of various species of particles provides information about the densities and temperature at which chemical equilibrium may occur. The STAR experiment has measured a variety of these particle abun-

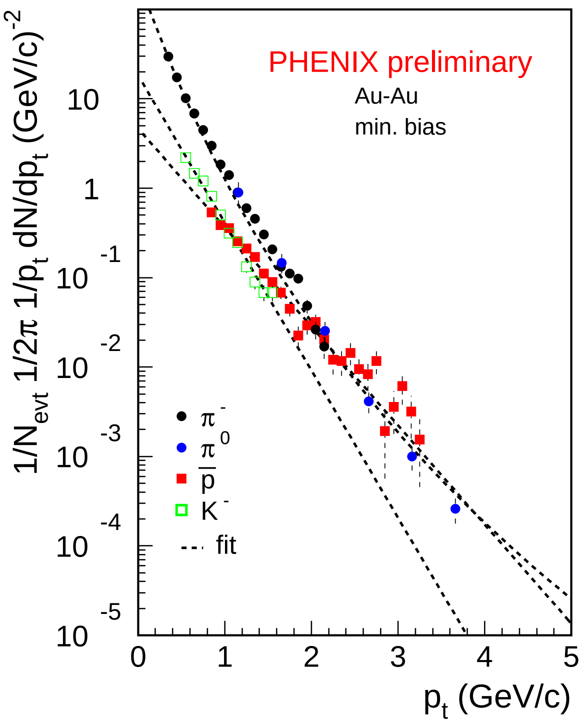

Figure 7: The composition of the transverse momentum spectrum.

dances. The relative abundances are consistent with a high degree of thermal equilibration,, as is shown in Fig. 9.

4.3 Hints for the Existence of a Quark Gluon Plasma

In fixed target heavy-ion collisions (160 GeV/A) at CERN several indications of the formation of hot (thermalized) partonic matter were observed. They include observation and characterization of J/ψ suppression, enhancement of strange hadrons, emission of direct photons and enhancement of low and intermediate mass dileptons.

Various proposed signals from a quark-gluon plasma have been examined at the CERN/SPS over the past five years:

4.3.1 J/Psi Suppression

The suppression of charmonium production can serve as a probe of the hot medium created in relativistic heavy ion collisions. A colored medium (i.e.

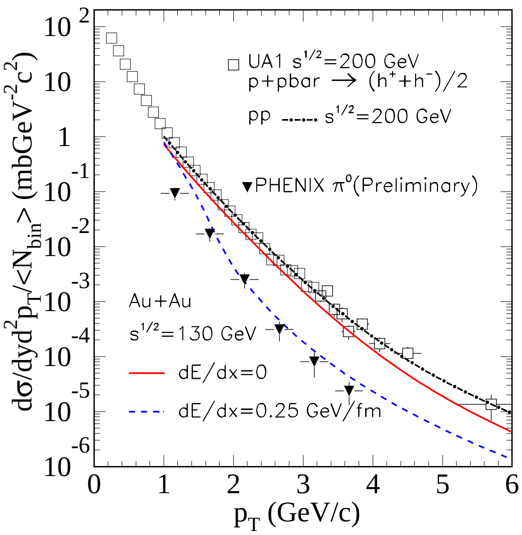

Figure 8: The preliminary data on hadron spectra in central $Au + Au$ collisions at $\sqrt{s} = 130$ GeV normalized by the geometrical binary collisions factor are compared with $p\overline{p}$ data at $\sqrt{s}$ =200 GeV and parton model calculations with and without parton energy loss.

a deconfined one) would break up a charm-anticharm quark pair created by hard nucleon-nucleon scatterings, thereby causing the charmonium state to melt. The melting depends on the energy density of the medium and the species of charmonium being considered, with the less tightly bound states breaking up at lower energy densities than the J/Ψ . NA50 observed just such an effect as shown in Fig. 10 Theoretical and experimental work was required to separate initial state effects on charmonium formation, final state breakup by ordinary hadronic matter (as observed in p-nucleus collisions, for example) and the medium effects of interest.

4.3.2 Low Mass Dileptons

Signatures that may be interpreted as evidence of chiral symmetry restoration were seen. In Fig. 11 the dilepton spectrum measured by NA45 at SPS/CERN, together with the expected spectrum from hadronic decays. The excess lepton pair yield at invariant masses between 200 and 800 MeV can be explained as a broadening and mass shift of the ρ meson due to the onset of chiral symmetry restoration. It is intriguing that competing interpretations of the data as arising from thermal radiation are also possible.

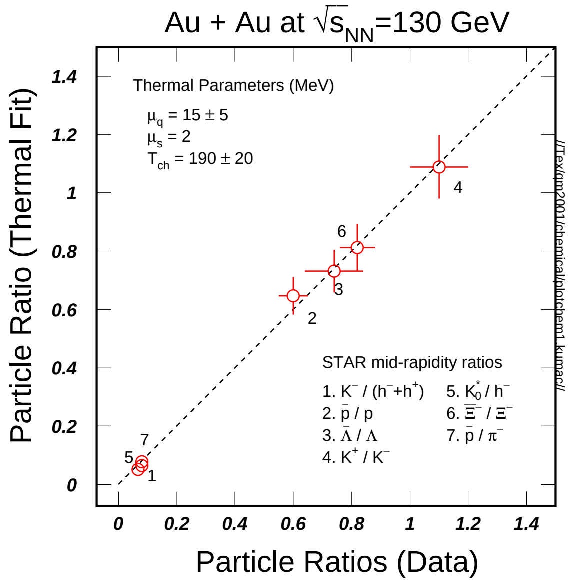

Figure 9: Particle ratios measured in experiment compared to a thermal fit.

4.3.3 Strangeness Enhancement

A state of free quarks is expected to show a strong enhancement of strangeness, particularly of anti-strange particles, whose yield would ordinarily be kinematically suppressed by their relatively large masses. Experiments at SPS/CERN, in particular WA97, see enhanced strange anti-baryon production, with increasing enhancement with each additional unit of strangeness. Experiments at the AGS, which have been able to detect only the anti-lambda, see a very strong enhancement in the anti-lambda to anti-proton ratio. Standard hadronic models cannot reproduce these results.

4.3.4 Pion Interferometry

Studies of particle abundances and spectra, as well as Bose-Einstein correlations (which give information about the space-time evolution of the collision) indicate that the system undergoes a state of rapid expansion and is close to both chemical and thermal equilibrium. Thermal equilibrium is thought to be reached very rapidly, but standard hadronic cross sections have difficulty accounting for the rapid rate at which this thermalization occurs. However, interaction cross sections arising from color among quarks are larger and

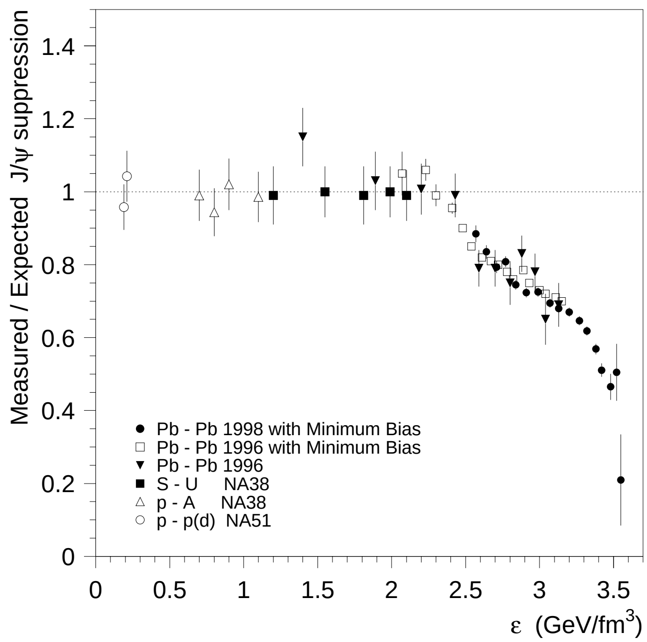

Figure 10: J/Ψ suppression as measured by NA50 at SPS/CERN.

could drive rapid thermalization.

4.4 Establishment of RIKEN-BNL Center

The RIKEN-BNL Center was established at Brookhaven National Laboratory. It also initiated the RIKEN-BNL fellows program and is deeply involved in the spin program at RHIC.

An important development over the course of the last LRP has been the establishment of RIKEN-BNL Research Center. This has proven to be a very successful collaborative effort between Japanese and US science. Founded by RIKEN lab in Japan which provides funding for the center, and headed by T. D. Lee, the center was established in 1997 to promote international collaboration in spin physics and physics of strong interaction at RHIC in general. The center implemented the RIKEN-BNL fellow program and thus far the program has created 13 bridged positions in universities and labs in the US and Canada. These RIKEN-BNL fellows will play a pivotal role in the high-energy physics community in the future. The RIKEN-BNL Research center has provided much needed catalyst for progresses in spin physics program and in the theory of high-energy heavy-ion collisions.

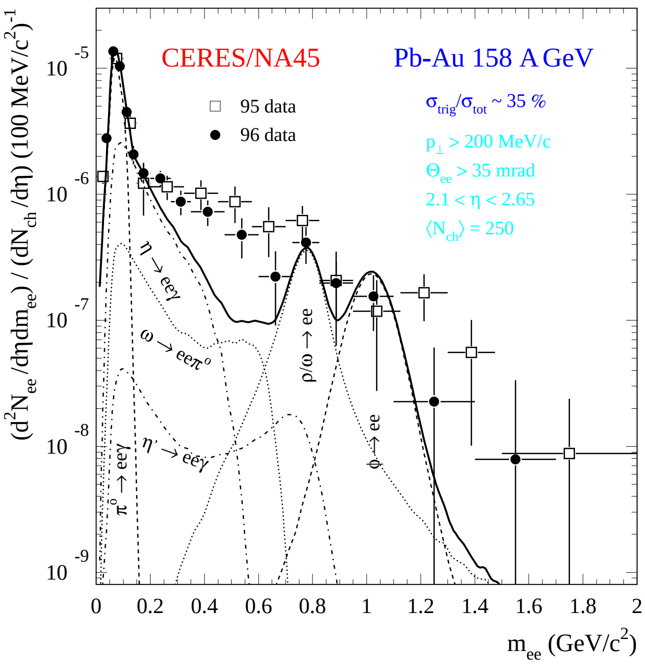

Figure 11: Dilepton spectrum measured by NA45 at SPS/CERN as compared to background from hadronic decay.

4.5 Color Superconductivity and the QCD Phase Diagram

Significant progress has been made in the theoretical understanding of the phases of QCD matter at high densities, such as color superconductivity and color-flavor locking.

Important progress has been achieved recently in understanding the possible phases of matter at low temperature and extremely high baryon densities where one can make a rigorous analysis by combining the BCS theory of pairing in condensed matter theory and the asymptotic freedom in QCD. A large gap (Δ 10-100 MeV) for quasi-particle spectrum in the color superconducting phase is predicted. New phases of matter, such as color-favor-locked phase, with remarkable properties are also predicted. They provide a theoretical laboratory within which chiral symmetry breaking and confinement can be studied at weak coupling. Those new phases will have interesting implications in our understanding of matter under extreme conditions. They also have significant astrophysical consequences on the physics in interiors of neutron stars.

4.6 Understanding of Initial Conditions for Heavy Ion Collisions and for Small-x Gluons

Progress have also been made in the theoretical understanding of the initial gluon distribution in large nuclei at small x and parton saturation which lead to predictions of initial conditions of high-energy heavy-ion collisions at RHIC.

With increasing gluon population at small fractional momentum x, the gluon density per unit transverse area becomes large and provides a natural scale in pQCD with weak coupling. Under such a weak coupling pQCD treatment of parton distributions in large nuclei becomes possible. A semi-classical treatment of gluon distributions in Weizsacker-Williams approximation is being developed. Under such a treatment, a nucleus can be considered as an ensemble of color charges and soft gluons are generated from coherent non-Abelian fields. Based on such effective theory, a generalized QCD evolution equations for gluon distribution at high densities was derived, which can reproduce both BFKL and DGLAP evolution equations in different limits. Numerical methods are developed to study the evolution of the initial strong gluonic fields. This not only enables one to calculate the gluon distribution at very small x and in a large nucleus but also allows one to estimate parton production and thus the initial conditions of high-energy heavy-ion collisions at RHIC.

4.7 Strange Matter and the H-Dibaryon

The possibility of strange quark matter on the microscopic level has been thoroughly investigated and strong limits have been established on the existence of a H-dibaryon and other strangelets.

A combination of complimentary H^0 dibaryon searches have combined to produce limits an order of magnitude more restrictive than the theoretical estimates for their production. A program to search for A=2-50 metastable strange quark matter in heavy-ion reactions, where small droplets of strange quark matter might be produced via the coalescence mechanism or through the formation of a QGP, was carried out at the BNL-AGS and CERN-SPS. Highly sensitive experiments using Au and Pb beams set 90% confidence level limits on strangelet production between 10^{-8} to 10^{-9} per central collision.

4.8 Nucleon Parton Distributions

4.8.1 Theoretical Accomplishments

The continuing development of next to leading order QCD for characterizing a variety of hard scattering cross sections has produced a highly consistent procedure for the extraction of nucleon parton distributions. Using a common set of parton distributions and coupling constants these NLO calculations produce agreement with measurement at the 10% level for a variety (DIS,DY) of hard scattering processes involving nucleons. Recent measurements that have provided new information on the nucleon's partonic structure are listed below.

4.8.2 Asymmetry in the Nucleon Sea

Drell-Yan measurements at Fermilab have mapped out the large asymmetry in the up, down sea of the nucleon. This large asymmetry indicates a large role for non-perturbative QCD in the creation of the nucleon sea. (Fig. 12)

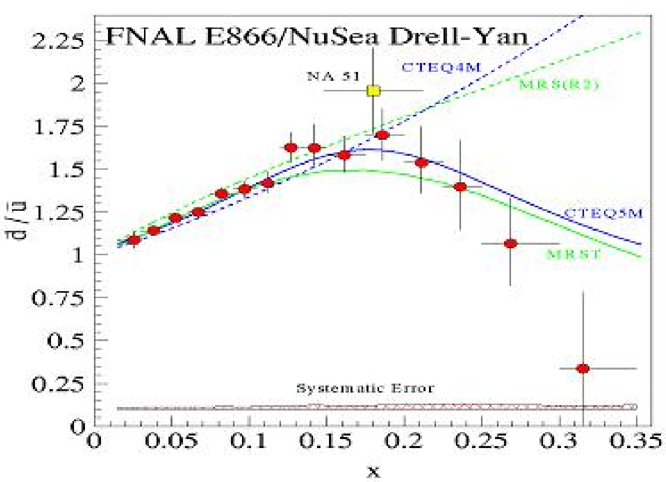

Figure 12: Asymmetry of up-down quarks in the sea of the nucleon.

Comparison of the Drell-Yan yields from hydrogen and deuterium showed that the neutron yield is 40% greater than that from the proton in the interval $0.1 < x < 0.2$. Using charge symmetry this requires that the down sea of the proton is nearly twice as large as its up sea in this interval. This represents the clearest evidence that the nucleon's parton distributions can not be generated from 3 constituent quarks at some low Q^2 and then appropriately evolved. This asymmetry in the sea must be put in by hand. Qualitatively the asymmetry can be ascribed to a $p + \pi$ configuration of the proton.

4.8.3 Gluon Distribution

Deep inelastic scattering of electrons from protons at HERA over a wide range of x and Q^2 has greatly expanded our knowledge of the nucleon's gluon distribution. The observed rapid growth of the nucleon's gluon density with decreasing x and increasing Q^2 has generated great interest in the saturation of parton densities. (Fig. 13)

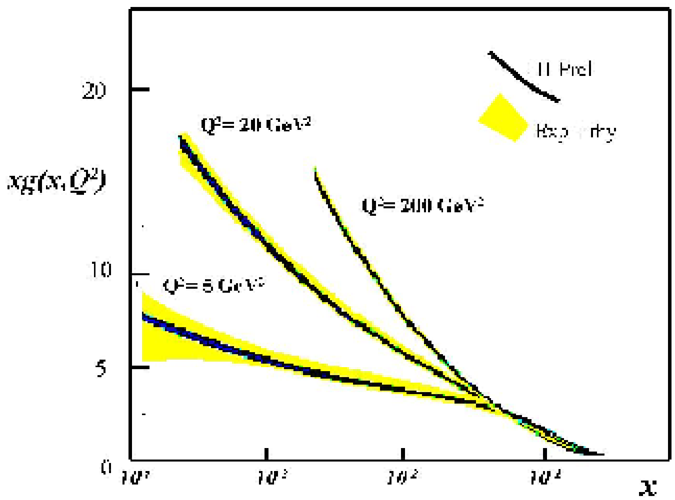

Figure 13: Rapid growth of gluon density at small x.

The high center of mass energy (300 GeV) of the DESY $e-p$ collider has allowed measurement of the gluon distribution of the proton down to $x \sim 10^{-4}$. The rapid growth observed in the gluon density at low x and high Q^2 naturally leads to the question as to where the parton distributions saturate. This saturated distribution should be characteristic of cold saturated gluonic matter, affect nuclear shadowing at very low x, and have a large impact on very high-energy heavy ion collisions. Saturation appears not to have been reached in these measurements.

4.8.4 The Spin Crisis Continues

Continuing measurement of the spin carried by the quarks and gluons in the nucleon at SLAC, CERN, and HERA have established the validity of the Bjorken sum rule to 10%. The same series of measurements find that only 1/3 of the spin of the nucleon can be found in the spin of its quarks. The deep inelastic scattering of polarized leptons from polarized nucleons allows one to measure the spin carried by the nucleon's partons. For the last decade a program of such experiments have been carried out at three laboratories (SLAC, CERN, DESY). Analysis shows the results from all the experiments to be mutually consistent and that the difference in the spin carried by up and down quarks is given by the Bjorken Sum Rule to within experimental error(10%). However the sum of the quark spins is only 1/3 much smaller than expected. The search for where this isoscalar spin may reside continues with the present suspects being gluons or orbital angular momentum.

5 Challenges for Experimental and Theoretical High Energy Nuclear Physics

5.1 Properties of Matter at the Highest Energy Densities

What are the gross properties of dense QCD matter? Is the basic idea that this is best described using fundamental quarks and gluons correct? RHIC addresses these questions by creating matter at the highest energy densities and allowing study of its properties and evolution. This involves delving into several closely connected questions: Is there a thermal stage during a heavy ion collision? If so, how does the temperature depend on the collision conditions, such as energy and impact parameter? Can we directly compare fundamental predictions to experimental data (e.g. for jet energy loss or lepton and photon radiation from the plasma)? Interpretation of experiments at lower energies has shown the importance of building a consistent theoretical picture, at least semi-quantitatively, for a wide variety of quark-gluon phenomena (such as enhanced strangeness production and J/ψ dissociation due to color screening in a quark-gluon plasma). Measurements of single hadron distributions and correlations reflect the dynamics of the collision, driven by pressure and density developed early in the collision. Penetrating probes, and probes which interact only electromagnetically so escape the dense system relatively unperturbed, yield information about the early stages of the collision. Sufficient event statistics in the suite of RHIC experiments, systematic analysis, and variation of the initial conditions are required to nail down the interpretation. This requires running RHIC at different energies of the beams to vary the initial temperature, and with different nuclei to vary the volume of dense matter.

5.1.1 What are the properties of QCD vacuum and QCD at high temperature and density?

Answering these questions by creating QCD matter at the highest energy densities involves delving into several closely connected questions: Is there a thermal stage during a heavy ion collision? If so, how does the temperature depend on the collision conditions, such as energy and impact parameter? Can we directly compare fundamental predictions to experimental data (e.g.

for jet energy loss or prompt lepton production)? Can we form a consistent picture, at least semi-quantitatively, for a wide variety of quark-gluon phenomena (such as enhanced strangeness production and J/ψ dissociation due to color screening in a quark-gluon plasma)? Is there a line of first-order transitions in the chemical potential-temperature plane, terminating on a critical point? Can such a critical point be observed via event-by-event fluctuations?

Experiments probe these questions via measurement of hadrons - single particle distributions and correlations among particles, and by detecting penetrating probes, which interact electromagnetically and therefore escape the dense system relatively unperturbed. Two-particle and multi-particle correlations reflect the dynamics of the dense matter, driven by pressure and density developed early in the collision.

It would be of great interest to determine the equation of state of the hot vacuum experimentally. Lattice gauge theory predicts nearly zero compressibility for an extended range of energy densities as matter is converted into the new phase, whereas once fully converted into the new phase the compressibility should jump to the plasma value of 1/3. A latent heat is expected to accompany this transition and has significant astrophysical implications. It is an important goal of the next few years to establish a better connection between modeling of the collisions and the measurements.

Measurement of collective dynamics via multi-particle correlations, such as used in flow analyses, can yield information on the pressure achieved and thereby the compressibility. Thermal radiation of photons or dileptons reflects the temperature history of the system.

5.1.2 Can evidence be found for the restoration of chiral symmetry?

Chiral symmetry is broken through the creation of a vacuum scalar condensate which couples to quarks and provides most of their mass. The challenge for RHIC measurements is to search for evidence of in-medium mass changes of the hadrons, associated with the restoration of chiral symmetry. Hints of this have been observed at the SPS, but a systematic study varying the initial conditions and system volumes has not yet been possible.

5.1.3 Does the J/Ψ production cross section tell us about deconfinement?

One of the most promising signatures for deconfinement of hot hadronic matter is the melting of the J/Ψ resonance. In the next few years, the PHENIX experiment at RHIC will provide measurements of J/Ψ production cross sections for a variety of nuclei and energies. The energy dependence of the cross section will be useful in sorting out various pictures of J/Ψ production. It is also very important to measure the D meson production.

For example, in the standard production of J/Ψ mesons by gluon fusion, the number of J/Ψ's is directly proportional to the number of $D's$. If on the other hand, there is sufficient number of $D's$ produced in the collision so that final state coalesence is important, then the number of $J/\Psi's$ is proportional to the number of D mesons squared.

5.1.4 What are the initial conditions for heavy ion collisions?

Understanding the initial conditions for heavy ion collisions will be very important for resolving various probes of the high density matter produced in heavy ion collisions. Jet's of high transverse momenta particles are produced very early in the collisions and can provide a probe of the matter at very early times. Hard scattering processes take place in those collisions between quarks or gluons (partons) in the initial state, before any thermalization can take place or quark-gluon plasma can be formed. In vacuum, hard scatterings produce either jets of particles with high transverse momenta or heavy quarks like charm or bottom, of which a small fraction materialize in bound c-cbar or b-bar states. Since the initially scattered partons must traverse the full space-time evolution of the reaction, they can serve as probes of the dense QCD matter. In particular, their energy as they traverse the dense matter yields information about the medium. Jet production can be computed quantitatively in QCD so that detailed comparison between theory and experiment is possible.

At the LHC, the typical time scales for the production of matter are expected to be shorter than that at RHIC. The typical energy scales of produced particles are correspondingly larger. Because of the larger energy scales and shorter time scales, the properties of matter may be describable theoretically using weak coupling methods in QCD.

5.1.5 Does the matter approach thermal equilibrium?

Real photons and virtual photons materializing as electron or muon pairs are radiated from the hot, dense QCD matter. While such radiation is emitted at all times during the collision, the reaction dynamics favors emission from the hottest part of the colliding system. Thus, measurement of the distribution of thermal radiation will yield the initial temperature. Such measurements require high statistics to separate the thermal radiation from large photon and lepton backgrounds arising from decays of the copiously produced hadrons. Systematic analysis, and variation of the initial conditions will be required to nail down the interpretation.

Measurement of the hard scattering processes via high pt hadrons and heavy flavor distributions will indicate to what extent the fast particles lose energy in the dense medium. This energy loss results in energy transfer from fast particles to the medium and drives thermalization. Furthermore, this energy transfer multiplies the number of gluons and therefore drives particle production, increasing the density of the medium further. In fact, predictions exist that the matter may reach the stage of gluon saturation. In such a case the physics is determined by interactions in a dense gluon gas, calculable using perturbative QCD, with subsequent hydrodynamic expansion. Measured particle yields, spectra and correlations to transverse momenta of at least 10 GeV/c pt are needed to see whether such predictions are correct. Presumably, particles with extremely high momenta will never thermalize, providing a built-in control measurement; the hadron pt spectra and correlations among fast hadrons will indicate at which point this becomes true.

Momentum and flavor distributions of the hadrons provide information on the degree of thermal and chemical equilibration when the colliding system becomes dilute enough that hadronic strong interactions cease. Combined with information from the medium probes and thermal radiation, the space-time evolution of the entire collision can be inferred. An important goal at RHIC is to determine whether equilibration occurs early in the collision, or only later, in the cooler hadronic phase. Combining hadronic observables with collective behavior reflecting early conditions, and thermal emission of virtual and real photons will become possible with the suite of experiments at RHIC.

5.1.6 How does the later, hadronic phase of the collision evolve?

Extensive study of heavy ion collisions at lower energy at the BNL AGS and CERN SPS have shown that the analysis of the distributions and correlations of soft hadrons yields the temperature and dynamics at the time the hadrons cease to interact, or freeze out. The space-time evolution thus measured is crucial to understanding the collision dynamics and to lending confidence in back-extrapolations to the early, hottest, phase of the collision. Systematic study of the conditions under which the hadrons freeze out, as a function of initial temperature and collision volume, will help to understand the underlying dynamics and sort out signatures of new physics from the underlying hadronic processes.

5.1.7 How is a nucleus different from a nucleon?

Not much data on elementary nucleon-nucleon collisions, nor on proton-nucleus collisions is available at RHIC energies. Such data are absolutely crucial as a baseline to interpretation of nucleus-nucleus data. Furthermore, the exciting physics available with polarized protons and probing parton distributions via p-nucleus collisions further drive the need to exploit this aspect of RHIC's capability.

5.2 What is the gluon field inside a heavy nucleus?

Do gluons and quark densities saturate and what are the implications for the physics of hot, dense matter and the formation of probes to discover new physics? Gluonic interactions should dominate the first few fm/c of heavy ion collisions, immediately following the initial nucleon-nucleon interactions as the nuclei penetrate one another. Gluon fusion processes dominate the production of charm and bottom quarks, as well as drive W production at energies attainable at RHIC. Consequently, measurements of open charm and bottom decays will likely be the most important ways to study the gluon fields inside heavy nuclei and their excitations in heavy ion collisions.

The Drell-Yan process of quark-antiquark annihilation probes the quark structure functions and indicates the extent of nuclear shadowing when measured in proton- nucleus collisions. If the gluon and quark densities can saturate, this will affect their distributions deep inside a heavy nucleus as well as the dynamics of the early stage of a heavy ion collision. Increased luminosity and enhanced detector capabilities will make RHIC an invaluable tool to study the evolution of the quark structure functions to small-x inside heavy nuclei (measurements of p-nucleus collisions will yield this information) and the evolution of the parton distributions during a heavy ion collision.

5.3 Gluons and Nucleon Spin

What contributions do gluons make to the nucleon spin? In contrast to matter at all larger distance scales, the field quanta inside hadrons play a crucial, dynamical role. Gluons contribute about half the mass and half the momentum of a nucleon. Do they also dominate the nucleon spin? It is clear from a decade of polarized deep inelastic scattering experiments that preferential spin orientation of quarks and antiquarks combine to account for much less than half of the nucleon spin. The first direct information on the gluon contribution is expected to emerge over the coming five years from two basic experimental approaches (see Fig. 14): measurement of polarized photon-gluon fusion processes with polarized lepton beams bombarding polarized fixed targets; and the study of polarized quark-gluon scattering processes utilizing the unprecedented access to a polarized proton collider at RHIC. Part of the answer will emerge only over a longer time scale: kinematic access to the abundant gluons that each carry less than 1% of the nucleon's momentum will require a new polarized electron-polarized proton collider.

5.4 Goldstone Bosons or Gluon Splitting?

What are the relative roles of Goldstone bosons vs. gluon splitting in the nucleon sea? Experiments over the past decade have revealed a large imbalance

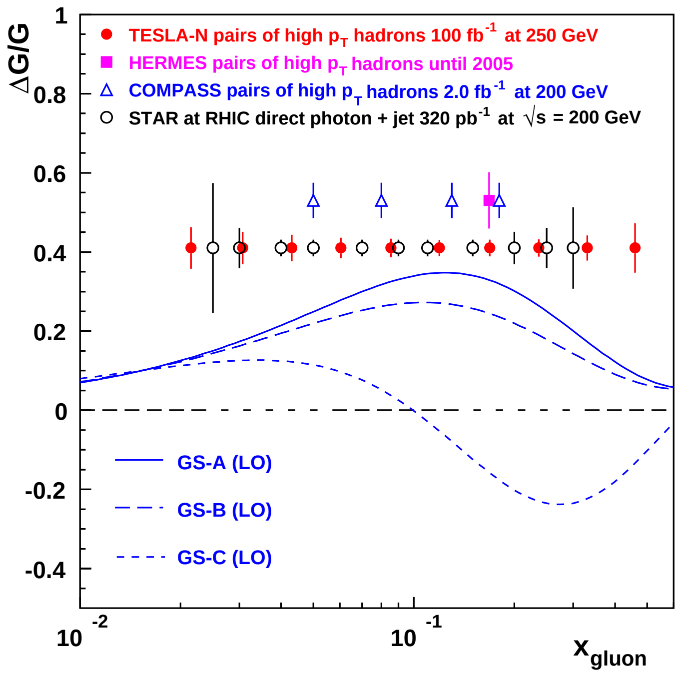

Figure 14: *Comparison of projected experimental results for gluon polarization to be obtained in two approved and one contemplated lepton-proton experiments in Europe vs. from direct photon production in polarized pp collisions at RHIC. The figure, taken from* hep-ph/0011299*, also shows three different models of gluon polarization, all consistent with the existing polarized deep inelastic scattering database. The addition of RHIC data at $\sqrt{s}$=500 GeV and from the PHENIX detector will significantly reduce the errors and expand the Bjorken x-range covered down to 0.01.*

between $\overline{u}$ and $\overline{d}$ antiquarks in the nucleon sea, suggesting that the sea arises in substantial part from a cloud of virtual pions. The antiquarks that appear in pseudoscalar mesons should be unpolarized. On the other hand, alternative approaches to modeling chiral symmetry breaking in low-energy QCD, which include $q\overline{q}$ excitation from the filled negative-energy Dirac sea, suggest that $\overline{u}$ and $\overline{d}$ antiquarks in a polarized nucleon should have large and opposite polarizations. The nature of the sea should be considerably illuminated over the coming five years by improvements in semi-inclusive deep inelastic scattering experiments and, especially, by studies of $W^{\pm}$ production in polarized proton collisions at RHIC, which will reveal the flavor-dependence of sea quark polarizations (see Fig. 15). Later collider measurements of electroweak production processes in coincidence with a forward nucleon of nearly beam momentum can probe the partonic content of the "meson cloud" more selectively.

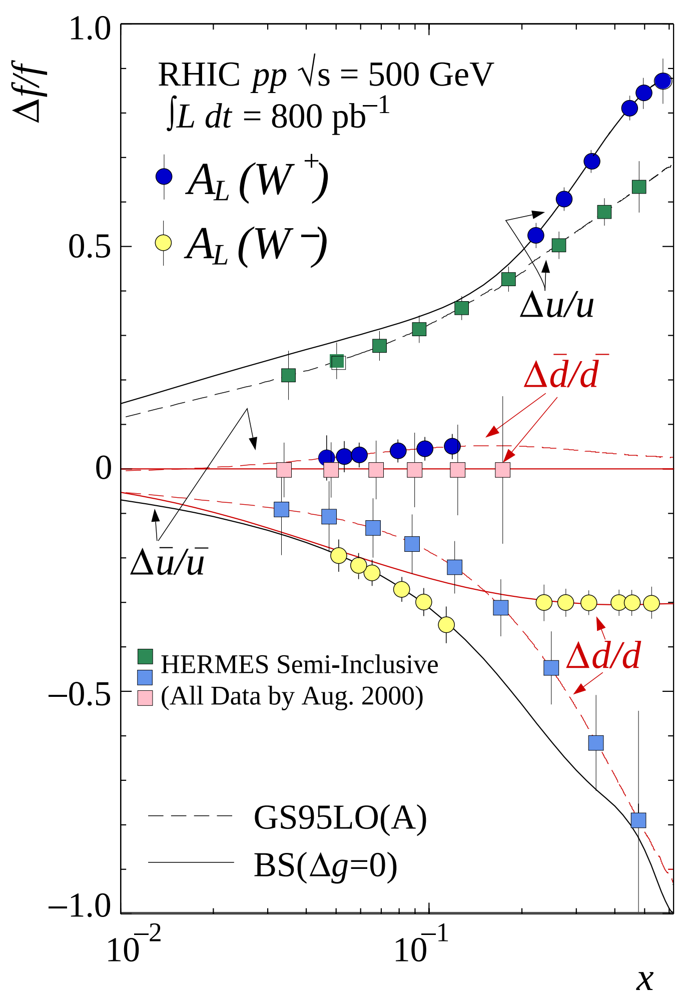

Figure 15: *The projected quality of information on the flavor-separated quark and antiquark polarizations in the proton that will be produced by semi-inclusive deep inelastic scattering measurements in HERMES at DESY and by $W^{\pm}$ production studies in polarized pp collisions with the PHENIX detector at RHIC. For viewing simplicity only, the data from different experiments are plotted along different model curves.*

5.5 Gluon Saturation and Colored Glass

Can one reach sufficiently high densities of gluons in hadronic matter to observe Bose-Einstein condensation? Deep inelastic scattering experiments at HERA have revealed gluon densities in the proton that are still rising rapidly at the lowest momentum fractions ($x_{Bjorken}$) and highest momentum transfer (Q^2) values yet probed. Will the gluon densities continue rapid growth toward even smaller momentum fractions, or will they saturate in this unexplored non-linear regime of QCD? The theory predicts Bose-Einstein condensation at sufficiently high gluon density, leading to a new state of matter called a "colored glass condensate." Over the coming decade, continuing work on the theory of high-density QCD will elucidate experimental signatures of this condensate. The most promising path to experimental investigation of this regime would exploit heavy nuclei to enhance the gluon density, in a high-energy $e - A$ collider. The essential properties of this collider and its detectors, needed to study unprecedented gluon densities, will be clarified over the coming five years. In parallel, measurements in $p - A$ collisions at RHIC should measure the poorly known gluon densities in nuclei for momentum fractions above 1%, the range of greatest relevance to the initial conditions in RHIC $A - A$ collisions.

5.6 Relativistic Effects of Quarks on the Nucleon Spin

How does the relativistic behavior of quarks inside a nucleon affect the quark spin distribution? The preferential orientation of quark spins along vs. opposite the nucleon spin can differ, as a result of relativity, between longitudinally and transversely polarized nucleons. This difference will be investigated experimentally for the first time in upcoming transverse spin measurements in both $\vec{e}-\vec{p}$ and $\vec{p}-\vec{p}$ collisions. Since all proposed measurements are sensitive to products of the unknown quark transverse spin preference ("transversity") with one or another second unknown (chiral-odd) factor, a decade of intertwined experiments is likely to be needed to pin down the transversity. This quantity is important additionally because it arises purely from quarks, in contrast to the flavor-singlet helicity preferences probed to date, where QCD mixes quark and gluon contributions.

5.7 Lattice QCD and Parton Structure Functions

Can lattice QCD calculations reproduce measured parton distributions in the nucleon? The best hope to check the consistency of emerging experimental information on nucleon structure with our understanding of QCD is via numerical solutions of QCD on a finite lattice of space-time points. Most lattice calculations of nucleon structure have been made to date employing the so-called "quenched" approximation, i.e., neglecting the excitation of flavorless $q\overline{q}$ pairs from the filled negative-energy Dirac sea. Such calculations show encouraging signs of (semi-quantitative) agreement with the measured (surprisingly small) fractions of the nucleon momentum and spin carried by quarks. However, before declaring this emerging agreement a success of QCD, it is critical to assess the poorly known impact of the quenched approximation. This issue can be addressed far more readily via calculations with the next generation of multi-teraflop computer clusters.

5.8 Stopping Power of Partons

What is the stopping power of partons in *cold* nuclear matter? Parton deconfinement has been predicted to lead to substantial changes in the energy loss of partons traversing the quark-gluon plasma, resulting in a softening of hadron spectra at high transverse momentum transfer that might serve as an experimental signature of QGP formation in $A-A$ collisions. Early hints of such effects in RHIC Au–Au collisions make it imperative to understand better how partons interact in *cold* nuclei. Relevant measurements can be made during the coming five years by studying several processes in $p-A$ collisions at RHIC or FNAL, which yield products that do not interact strongly. For example, the energy loss of quarks traversing normal nuclear matter can be inferred for the entrance channel in Drell-Yan dilepton production, from the A-dependence of the cross section as a function of the quark momentum fraction in the proton. Alternatively, the production of a high momentum quark inside nuclear matter can be tagged, and its subsequent fragmentation tracked, by coincident prompt photon production.

5.9 Partons and the Nucleon Wavefunction

What correlations among different partons are encoded in the nucleon wave function? In a major theoretical development of the past five years, the concept of parton distributions that depend on $x_{Bjorken}$ and Q^2 has been generalized to three-dimensional amplitudes. These generalized parton distributions (GPD's) provide a theoretical link between structure functions measured in deep inelastic scattering and electroweak form factors of the nucleon measured at lower energies. Experimental delineation of the GPD's will require a new generation of measurements of deeply inelastic exclusive processes, both virtual Compton scattering and meson production. Such measurements will begin over the next five years and could be studied efficiently at relatively low momentum transfers at an energy-upgraded CEBAF. However, full access to spin measurements at momentum transfers where scaling is expected to be applicable requires a high-luminosity $\vec{e}-\vec{p}$ collider.

6 High Energy Nuclear Physics in the U. S. and the Rest of the World

Physicists from the U.S. play a key role in the exploration of the properties of nuclear matter under extreme conditions of temperature and density. This area of research, both in theory and experiment, is also the focus of substantial effort in Europe, Japan and other parts of the world. Since the Bevalac era, the U.S. has participated in experiments at both the Alternating Gradient Synchrotron (AGS) at Brookhaven laboratory, and at CERN. With the recent successful inaugural run of RHIC, the U.S. assumes leadership in high energy nuclear physics.

Before RHIC, the highest energy heavy ion collisions produced in the laboratory were available at CERN. These experiments had predominantly European participation, although many experiments such as NA44, NA49, and WA98, had a significant U.S. presence. The results of this program were quite suggestive, culminating in the announcement of a possible first observation of the quark-gluon plasma. While many critical issues are still to be resolved with planned experiments at SPS, the world attention has now clearly moved to RHIC experiments which should settle many unanswered questions and open up new frontiers in the study of the dense new phase. This is an example of the complementary nature of the relativistic heavy ion programs at RHIC and CERN. Both have benefited from a free flow of ideas between the two, with U.S. and European physicists working on experiments at both laboratories. This trend is expected to continue in the future, with European physicists participating fully in all four RHIC experiments. Once the LHC is commissioned in 2007, the highest energy heavy ion beams will once again be available at CERN and it is expected that the mutually beneficial interaction between the two communities will continue.

Understanding hadron structure at the partonic level is a major effort of physicists in North America, Europe and Japan. U.S. efforts in these studies have been complementary to other global efforts, with comparable impact. For example, a Fermilab experiment led by nuclear physicists from Los Alamos and other American institutions provided the definitive evidence of the flavor imbalance in the nucleon sea, while experiments at HERA, with predominantly European participants, have provided the critical data regarding nucleon structure functions at very low momentum fraction. The major contributions to date in studies of nucleon spin structure have come from polarized deep inelastic scattering experiments carried out at CERN, SLAC and DESY, in each case with significant involvement of U.S. nuclear physicists in the collaborations. The major European efforts for the short-term future are concentrated on the HERMES and COMPASS experiments. American involvement in HERMES remains substantial, though it is reduced from several years ago, while there is negligible American involvement in COMPASS. The RHIC Spin program provides the opportunity for the U.S. community, with critical collaboration and financial support from Japan, to have a major impact on these scientific questions with a unique facility and experimental approaches that complement the ongoing lepton-beam fixed-target experiments in Europe and those recently approved at SLAC.

The longer-term goals of extending partonic spin sensitivity to very low or very high x, and of mapping out correlations among partons within the framework of Generalized Parton Distributions (GPD's), will require new or upgraded accelerator facilities. Discussions in Europe center on three possibilities: polarizing the proton beam in HERA to provide a polarized ep collider (viable only if the TESLA project at DESY is not approved); bombarding fixed polarized targets with a polarized 250 GeV lepton beam from TESLA (the TESLA-N project); and the ELFE accelerator that would provide continuous polarized electron beams up to 25 GeV to bombard fixed targets. The goals of these projects overlap at least partially those of the JLab upgrade to 12 GeV and of the proposed electron-ion collider in the U.S. The CEBAF upgrade is a more cost-effective solution than ELFE, but with considerably less kinematic reach into the anticipated scaling regime for GPD's. Polarizing the protons in HERA would be far more cost-effective than constructing a new e-p collider in the U.S., and would provide access to spin structure at lower x, but would have far less luminosity for exploring semi-inclusive and exclusive processes, as well as for the critical e-A collision program to search for saturation of gluon densities at low x.

There has also been a growing interest in theoretical problems in high-energy nuclear physics throughout the world. Much of the interest is mostly motivated by the desire to understand the structure of matter at extreme conditions and in uncharted regimes of kinematics made available by major facilities in the US and Europe. There are strong collaborative efforts among theorists in the US and other countries in every aspect of the theoretical studies in high-energy nuclear physics. One coordinated collaboration worth of mentioning is the Hard Probes Collaboration which has been providing much needed theoretical inputs to experimentalists throughout the world. The establishment of RIKEN-BNL Research Center, especially the hiring of more than 10 RIKEN fellows, will strengthen the US theoretic effort in the future if enough funds can be secured to support these the research of these RIKEN fellows at the end of their bridged period.

7 Resource and Manpower Requirements

In the course of developing input for the discussion at the Brookhaven Town Meeting, and the consensus reached for the recommendations given above, a number of workshops were held and white papers were prepared in which the resources required to achieve the goals of this subfield were assessed. These are documented in five white papers that can be found on the web at www.bnl.gov/rhic/town meeting. They are as follows:

1: Exploring QCD at High Energy Density using Heavy Ions at RHIC

2: RHIC Spin Physics Program

3: White Paper on Proton-Nucleus Collisions

4: White Paper on Electron-Ion Collisions

5: Heavy Ion Collisions at the LHC

In addition to these white papers, presentations were heard at the Town Meeting regarding the needs, in general, for support of nuclear theory in view of the array of important scientific questions confronting the field.

Here, based on this more detailed input, we outline the resources that will be needed throughout the long range planning period to realize the scientific goals set forth in this report. The presentation is structured along the lines of the recommendations above, which are indicative of the priorities for this subfield. Guided by the charge to NSAC, we take as a basis the FY 2001 level of funding and manpower, and discuss the incremental resources needed to achieve the goals for high energy nuclear physics over this period. We also discuss the implications for the subfield if support were to remain constant at the FY2001 level of effort. The table below, which is taken from White Paper 1, summarizes proposed plans for equipment funding to upgrade the RHIC machine and detectors during the long range planning period.

7.1 Resources and manpower: Recommendation 1

7.1.1 Full operation of the RHIC facility

RHIC is the primary U.S. facility to carry out this program, and its full exploitation calls for 37 weeks per year of operations (rings cold) and 15 weeks for shutdown maintenance and improvements. This annual cycle has been the agreed-upon planning basis s by DOE and BNL since an NSAC review of the RHIC operations plan in 1996. The present budget for operations, $103M per year in FY 2001, is based on this 1996 NSAC plan, but falls well short of the 37 week target. A BNL analysis of real-life experience operating RHIC shows shows that steady-state operation for 37 weeks per year will require a $15M step in annual operating funds. If funding were to proceed without this step, at a constant-effort level based on FY 2001, Brookhaven

********* PROPOSED *********
Long Range equipment funding plan for RHIC Upgrades
Machine and Detectors… FY 2002 M$

***A.** This continues the existing rate of detector equipment funding:*
Implement planned detector upgrades to accommodate short-term luminosity improvements

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	Total
Short-term improvements	8.0	8.0	8.0	6.0							30.0

***B.** This is the RHIC-II luminosity upgrade initiative: machine (electron cooling) and detectors, including R&D:*

Luminosity upgrade [RHIC II]	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	Totals
Electron Cooling				2.0	15.0	15.0	15.0	7.0			54.0
RHIC II Detector Upgrades				5.0	10.0	15.0	15.0	15.0	10.0	10.0	80.0
Subtotals		0.0	0.0	7.0	25.0	30.0	30.0	22.0	10.0	10.0	134.0
RHIC II R&D [Operating funds]											
Machine R&D		1.0	2.0	3.0							6.0
Detector R&D	0.5	1.0	2.0	2.0	1.0	1.0	0.5				8.0
Subtotals	0.5	2.0	4.0	5.0	1.0	1.0	0.5				14.0
Total RHIC II	0.5	2.0	4.0	12.0	26.0	31.0	30.5	22.0	10.0	10.0	148.0
Total Upgrades	8.5	10.0	12.0	18.0	26.0	31.0	30.5	22.0	10.0	10.0	178.0

This is the assumed ramp-up of luminosity from the Au-Au design value…
The first factor of 4 is funded from the on-going operations budget. The final factor of 10 is RHIC II:

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
Au-Au Luminosity	L_0	$2xL_0$	$4xL_0$	$4xL_0$	$4xL_0$	$4xL_0$	$4xL_0$	$4xL_0$	$40xL_0$	$40xL_0$

has determined that RHIC will be limited to 24 weeks of cryogenic operation per year, which translates to 18 weeks of colliding beams. This would be achieved by allowing only minimal capital improvements to the operations infrastructure, with consequent risk to the overall machine efficiency.

7.1.2 Adequate support of experimental and theoretical research

It was pointed out at each of the Long Range Plan Town Meetings that new facilities (e.g. RHIC) have vastly increased the number of scientific questions being addressed in the field. There has been no corresponding increase in theory manpower, in spite of the extraordinary increase in the range of important problems in nuclear physics that can be theoretically addressed within the framework of QCD and which are of vital significance to the planned experimental program. For example, lattice gauge theory has become an important means for addressing some of these questions, but is largely not supported by nuclear theory. In order to bring the overall effort in nuclear theory to a level commensurate with the current scientific challenges in the field, it is estimated that the number of theory FTEs should double over the LRP period. This would require an increase of the theory budget for the entire field of nuclear physics by $15M over the ten year period of this long-range plan, an increment of about $1.5M per year.

Support for experimental researchers at RHIC has been good over a period of intense activity in the development, construction, and commissioning of a complex suite of detectors, while in parallel maintaining a strong effort to develop the tools and procedures to reconstruct and analyze huge volumes of data. The value of this capability was clearly demonstrated by the remarkable speed with which detailed physics results became available from the first data run. This strength must be maintained to ensure productive utilization of the long data runs to come, while at the same time carrying out planned improvements in the capabilities and performance of the detectors.

Under a constant effort scenario, the theory effort will remain disproportionately low, with resultant risk of missed opportunities and inadequate realization of the full scientific potential of RHIC and other facilities. Experimental manpower levels may erode if the goal of full operation of RHIC is not achieved.

7.1.3 Near-term upgrades to the RHIC detectors

During the next few years, as experience is gained with operation of the machine at its full design performance, the luminosity is expected to be improved by a factor of four over its design value. The means for this improvement in luminosity is already incorporated in the design of the collider, and no new construction funds are required to implement it. In the meantime, several moderate-scale upgrades to the existing RHIC detectors are planned over the next five years to further extend their physics capabilities as the exploration of this new energy regime moves forward. These upgrades are on the scale of the Additional Experimental Equipment (AEE) projects, which are now reaching completion. The proposed funding plan is shown in the accompanying table.

Under a constant effort scenario, the first priority would be to run the program with the existing detectors to the maximum degree possible. Two important on-going projects, the STAR EM calorimeter (barrel and endcap) and the PHENIX muon arms, would be completed as planned, but only a very limited menu of essential new projects (such as upgrades to the data acquisition and trigger systems to accommodate improving luminosity) would be undertaken.

7.2 Manpower and resources: Recommendation 2

The proposed R&D funding to enable an order-of-magnitude upgrade of the luminosity for heavy ion beams in RHIC by the end of this long-range planning period is shown in part B of the table. (RHIC II R&D funds). The machine component of this R&D is specifically tailored to the development of electron cooling of the circulating ion beams. The detector R&D is planned to be a proposal-driven program to support major upgrades to the RHIC detectors to allow them to take full physics advantage of this luminosity upgrade. A number of candidate detector projects are discussed in White Paper 1. The estimated costs, and proposed funding profile, for constructing the RHIC II upgrades are also given in the table.

R&D for an electron-ion collider is discussed in White Paper 4. The effort involves the development of a high energy, high intensity electron beam with energy recovery; lattice design for electron-ion collision regions under various scenarios; and the development of detector techniques and designs for these collisions. The funding required for this R&D program is approximately $5M per year over a period of 4-5 years. In order to provide effective guidance for planning a possible construction initiative near the end of this long-range planning period, this R&D should be initiated as soon as possible.

Under a constant effort scenario, major upgrades for RHIC, or a new accelerator initiative such as the electron-ion collider, would necessarily be delayed, and probably not be realized during this long-range planning period.

7.3 Manpower and resources: Recommendation 3

Proposals by Brookhaven, Jefferson Lab, and Fermilab are being prepared as a part of the DOE Office of Science initiative, Scientific Discovery through Advanced Computing (SciDAC). Funding for such a facility is expected to be incremental to the nuclear physics program budget. The question of operational costs and responsibilities requires more study as the proposal moves forward. The implementation of such facilities has direct implication for the level of nuclear theory manpower, addressed in recommendation 1.

Under a constant effort scenario, if the SciDAC initiative succeeds, this new opportunity for nuclear physics would further stress the theory resources.

7.4 Manpower and resources: Recommendation 4

As discussed in White Paper 4, the expected level of participation in the LHC heavy ion program by U.S. scientists is not expected to require major investments in detector hardware. The required equipment funding would be at the level of $10M over the next 3-4 years. The proposed commitment of scientific manpower would be about 10% of the involvement in RHIC experiments, i.e. about 50 U.S. scientists. This would continue a long-standing, mutually beneficial interaction between U.S. and European scientists in this field. It is expected that some participation in the LHC effort, if only on a very modest scale, would proceed even under a constant effort scenario.

7.5 Appendix A: Town Meeting on Nuclear Matter and Hadrons at High Energies Brookhaven National Lab January 21-23, 2001

Agenda

Sunday, Jan. 21

Chair: T. Hallman

9:00	Welcome and introduction	P. Paul
9:15	Remarks from DNP	H. Robertson
9:30	QCD and Heavy Ions: perspective	D. Kharzeev
10:30	Break	
10:45	White paper on RHIC II	B. Jacak, T. Ludlam
11:45	White paper on participation in LHC heavy ion program	U. Heinz, G. Odyniec
12:30-2:00	Lunch	

Chair: S. Aronson

2:00	White paper on pA at RHIC	J.-C. Peng
2:45	White paper on RHIC Spin	R. Jaffe, G. Bunce
3:45	Break	
4:00	White paper on Electron-Ion Collider	R. Milner
4:45	QCD and hadronic physics: report from the Sanderling workshop	X. Ji
6:00	Reception (Berkner Hall)	
7:00	Dinner (Berkner Hall)	

Monday, Jan. 22

Chair: J. Schukraft

9:00	Theory presentation	B. Gibson
9:45	Computing initiative for QCD calculations	N. Christ
10:30	Break	
10:45	The long range planning process in nuclear physics: A perspective.	P. Bond
11:30	Nuclear Physics at BNL	T. Kirk
12:00	A possible future for the BNL accelerator complex	S. Ozaki
12:30	Lunch	

Chair: L. Schroeder

2:00	Short contributions from the community:	
	W. Guryn	The pp2pp experiment
	P. Braun-Munzinger	Charmonium production at LHC
	M. Tokarev	Z-Scaling and high pt physics at RHIC
2:45	Discussion of priorities	B. Müller, discussion leader
5:30	Adjourn	
Evening	Organizing Committee meets to discuss priorities and outline the final white paper. (Berkner Hall, Rm. C)	

Tuesday, Jan. 23

Chair: R. Pisarski

9:00	Education/Outreach: the role of national laboratories	J. Marburger
9:45	Education/Outreach: the role of universities	W. Bauer
10:30	Break	
10:45	Discussion of priorities and final white paper L. McLerran, discussion leader	
12:30	Town Meeting adjourns	
Afternoon	Organizing committee meeting to discuss writing of white paper (Room 2-160, Physics Bldg.)	